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Surface plasmon excitation by normally incident light on surface-relief metallic diffraction gratings is studied numerically. Predominantly unidirectional excitation is achieved with a grating of either a slanted lamellar or an inclined sinusoidal groove profile, both having shallow depths. Maps of Poynting vector illustrate that the energy flow turns from normal incidence in the far-field region to a pattern almost parallel to the grating surface in the required direction of excitation of a single SPP wave.

OCIS codes: (240.6680) Surface plasmons, (050.1950) Diffraction gratings

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References and links

1. R. W. Wood, "On a remarkable case of uneven distribution of light in a diffraction grating spectrum," Phylos. Mag. **4**, 396-402 (1902)
2. U. Fano, "The theory of anomalous diffraction gratings and of quasi-stationary waves on metallic surfaces (Sommerfeld's waves)," J. Opt. Soc. Am. **31**, 213-222 (1941)
3. A. Hessel and A. A. Oliner, "A new theory of Wood's anomalies on optical gratings," Appl. Opt. **4**, 1275-1297 (1965)
4. H. Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings* (Springer-Verlag, Berlin, 1988)
5. D. A. Weitz, T. J. Gramila, A. Z. Genack, and J. I. Gersten, "Anomalous low-frequency Raman scattering from rough metal surfaces and the origin of the surface-enhanced Raman scattering," Phys. Rev. Lett. **45**, 355-358 (1980)
6. T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays," Nature **391**, 667 – 669 (1998)
7. S. Enoch, E. Popov, M. Nevière, and R. Reinisch, "Enhanced light transmission by hole arrays," J. Opt. A: Pure Appl. Opt.. **4**, S83-S87 (2002)
8. E. Popov, N. Bonod, M. Neviere, H. Rigneault, P.-F. Lenne, P. Chaumet, "Surface plasmon excitation on a single subwavelength hole in a metallic sheet," Appl. Opt. **44**, 2332-2337 (2005)
9. W. L. Barnes, A. Dereux, T. W. Ebbesen, "Surface plasmon subwavelength optics," Nature **424**, 824-830 (2003)
10. E. Ozbay, "Plasmonics: merging photonics and electronics at nanoscale dimensions," Science **311**, 189-193 (2006)
11. E. Devaux, T. W. Ebbesen, J.-C. Weeber and A. Dereux, "Launching and decoupling surface plasmon via micro-gratings," Appl. Phys. Lett. **83**, 4936-4938 (2003)
12. D. Egorov, B. S. Dennis, G. Blumberg and M. I. Haftel, "Two-dimensional control of surface plasmons and directional beaming from arrays of sub-wavelength apertures," Phys. Rev. B **70**, 033404 (2004)
13. J.-Y. Laluet, E. Devaux, C. Genet, J.-C . Weeber, A. Dereux, "Optimization of surface plasmons launching from subwavelength hole arrays: modelling and experiments," Opt. Express **15**, 3488-3495 (2007)
14. F. López-Tejeira, S. G. Rodrigo, L. Martín-Moreno, F. J. García-Vidal, E. Devaux, T. W. Ebbesen, J. R. Krenn, I. P. Radko, S. I. Bozhevolnyi, M. U. González, J. C. Weeber, A. Dereux, "Efficient unidirectional nanoslit couplers for surface plasmons," Nature Phys. **3**, 324-328
15. M. Neviere, "The homogeneous problem," in *Electromagnetic theory of gratings,* R. Petit ed. (Springer-Verlag, 1980), ch.5

16. B. Wang, J. Jiang, and G. P. Nordin, "Compact slanted grating couplers," Opt. Express **12**, 3313-3326 (2004)
17. M. Nevière and E. Popov, *Light Propagation in Periodic Media: Diffraction Theory and Design* (Marcel Dekker, New York, 2003).
18. T. W. Preist, J. B. Harris, N. P. Wanstall, and J. R. Sambles, "Optical response of blazed and overhanging gratings using oblique Chandezon transformations," J. Mod. Opt. **44**, 1073-1080 (1997).
19. L. Li, "Oblique-coordinate-system-based Chandezon method for modeling one-dimensionally periodic, multilayer, inhomogeneous, anisotropic gratings," J. Opt. Soc. Am. A **16**, 2521-2531 (1999).
20. E. Popov, L. Tsonev, D. Maystre, "Gratings-general properties of the Littrow mounting and energy flow distribution," J. Mod. Opt. 37, 367-377 (1990)

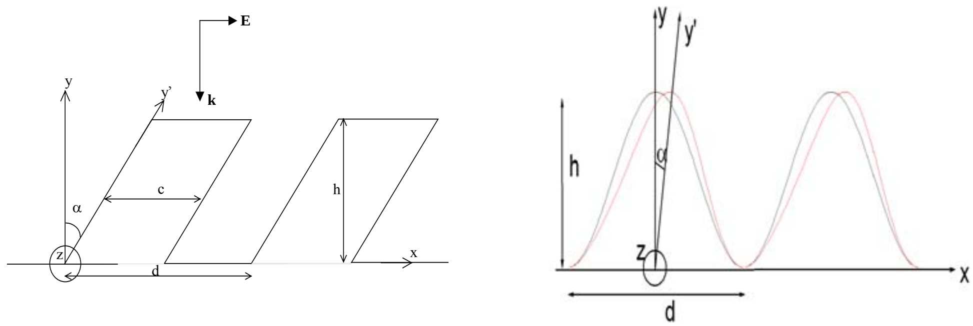
1. Introduction

Excitation of surface plasmon-polaritons (SPP) by diffraction gratings became a subject of interest in optics since the discovery of diffraction efficiency anomalies by Wood [1] more than a century ago, although the role of SPP in these anomalies was clarified much later [2, 3]. This phenomenon has been a subject of extensive interest to grating users and manufacturers in the 1980s [4], and became particularly important for its role in surface-enhanced Raman scattering (SERS) [5]. SPP are found responsible for the enhanced transmission through subwavelength aperture arrays [6, 7] or single apertures [8], structures which are currently in the centre of intense researches and applications in many scientific areas from physics to biology and chemistry where the matter-light interaction has to be increased [9]. They can also be used as optical signal carriers on metallic surfaces [10]. However, to conceive highly integrated photonic/electronic circuits, the launching of SPP, i.e. the coupling between light and SPP, has to be highly efficient [11 - 14]. As the propagation constant of SPP is greater than that of the cover dielectric, gratings or prisms are used to phase-match the incident light to SPP. In order to decrease the diffraction losses, the grating period has to be sufficiently small as to support only the zeroth propagating orders. Efficient coupling can be made to the SPP wave propagating in a given direction in non-normal incidence, so that a single evanescent diffraction order is phase-matched to the SPP wave [13, 15]. However, many plasmonic applications require normal incidence. Unfortunately, with a grating of symmetrical profile in normal incidence SPP propagating in the two opposite directions are equally excited. Recently, Lopez-Tejeira et al. [14] have proposed to use back-side slit-illumination and a Bragg mirror made of periodic grooves on one side of the slit in order to reflect one of the two counter-propagating surface plasmon modes. However, this structure requires back-side illumination and it is less efficient when compared with diffraction gratings.

A similar problem has arisen in integrated optics when efficient guided-mode excitation in dielectric waveguides is needed. One possible solution is to break the symmetry of the structure so that, even in normal incidence, the excitation of the counter-propagating waveguide modes happens in an uneven manner [16]. To this aim, an asymmetrical groove profile can be used, an approach that we extend in this paper to metallic gratings and surface plasmon-polariton excitation.

2. Surface plasmon excitation with slanted gratings

Gratings depicted in Fig. 1 are studied with the differential method [17] which relies on reduction of Maxwell equations to a set of first-order differential equations. Integration from the substrate to the superstrate is made in both cases (lamellar and sinusoidal) with the use of the eigenvalue/eigenvector technique [17]. In the lamellar case, the rigorous coupled-wave method is used and the integration is made along the y' ordinate (see Fig. 1). The inclined sinusoidal grating is modelled with the C method in an oblique coordinate system [18,19] in which the grating profile function is purely sinusoidal with respect to the y' axis.



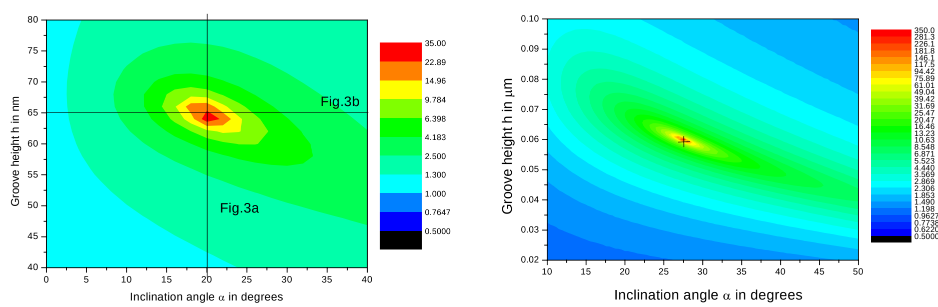
(a) (b)

Fig. 1. Slanted gratings of period d made of aluminium with refractive index n = 1.378 + i 7.616, illuminated in normal incidence in TM polarization with a wavelength λ = 632.8 nm.

a. Lamellar grating : groove width c, groove height h, inclination angle α;
b. Sinusoidal grating: groove height h, inclination angle α.

In the superstrate (air) above the corrugated region, the electromagnetic field can be expressed in the form of Rayleigh expansion. The incident field is chosen in TM polarization and the z-component of the magnetic field of the nth diffracted order writes: $H_{z,n}^{\pm}\exp(i\beta_n y)$, where β_n is the y-component of the propagation constant of the nth order, and $H_{z,n}^{\pm}$ are the magnetic field amplitudes of the z-component of the magnetic field (of the nth order) propagating in the ±y direction. The incident field is normalized so that $H_{z,0}^{-} = 1$.

The SPP propagating along the negative x axis is chosen to be excited. The incident energy has to be transferred into the SPP through the –1st order. As a consequence, the –1st evanescent order has to be optimised. What is required for unidirectional SPP excitation excited through the –1st order is to maintain the lowest possible amplitude in the 0th and +1st orders, and the highest amplitude in the −1st order. Thereby, the first part of the study consists of calculating the three amplitudes $H_{z,1}^{+}$, $H_{z,0}^{+}$ and $H_{z,-1}^{+}$ as functions of the period, the inclination angle, the groove width and the groove depth, and to optimize the ratio of the −1st order to the +1st order and to minimize the 0th order. Figure 2 displays the ratio of the +1st order to the −1st order as a function of the groove height and the inclination angle, with a previously optimized period. In both cases, a high ratio can be achieved for shallow gratings, with a groove depth around 65 nm, and an inclination angle in the range 20°-30°, and a period around 0.6 μm.

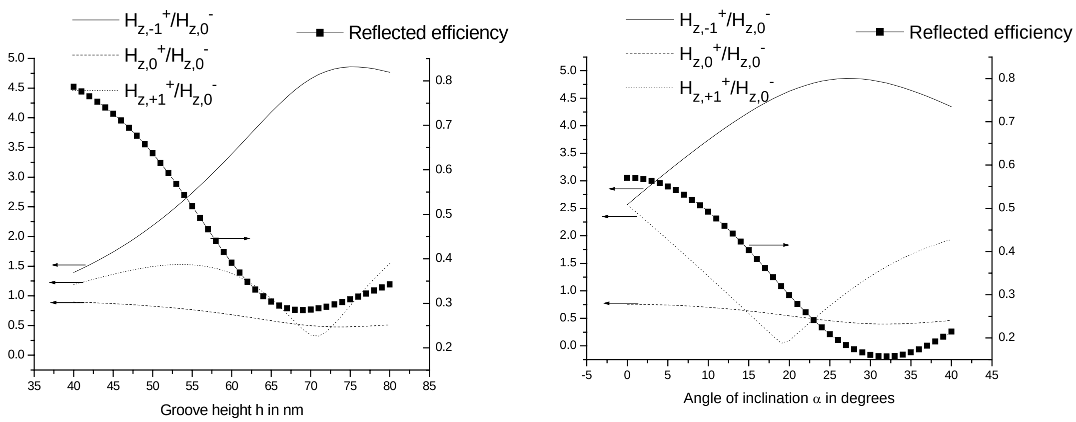


(a) (b)

Figs.2. Amplitude ratio of the −1st to the +1st order as a function of the groove height h and the inclination angle α. a) lamellar geometry, d = 600 nm. b) sinusoidal geometry, d = 627 nm.

Once it has been shown that a high amplitude ratio can be achieved with shallow gratings, we have tried to demonstrate that a very low 0th amplitude can be obtained. For that purpose,

Fig. 3 presents the three normalized amplitudes of the +1st, 0th and –1st orders and the reflected efficiency as functions of *h* (Fig. 3a) and α (Fig. 3b), which correspond to the two black lines in Fig. 2a.



Figs. 3. Lamellar grating with d = 0.6 μm, c = 0.4d, λ = 632.8 nm. Left vertical axis: normalized $H_{z,1}^+/H_{z,0}^-$, $H_{z,0}^+/H_{z,0}^-$ and $H_{z,-1}^+/H_{z,0}^-$ amplitudes of the –1st, 0th and +1st reflected orders, respectively, as a function (a) of the groove height *h* (with α = 20°) and (b) the inclination angle α (with *h* = 65 nm). Right vertical axis: reflected efficiency.

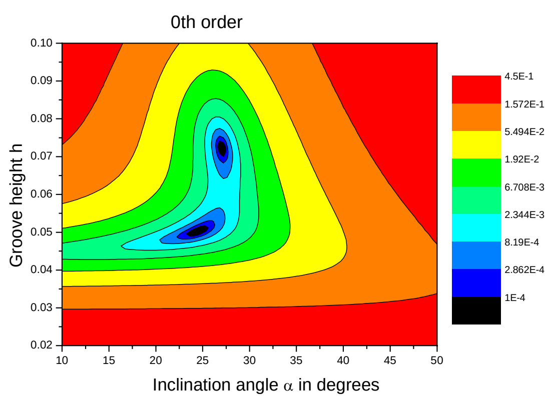


Fig. 4. Sinusoidal grating. The 0th-order amplitude as a function of *h* (in μm) and the inclination angle α (in degrees).

When the inclination angle is null, the amplitudes of the -1st and +1st orders are equal, as expected for symmetrical gratings (see Fig. 3b). At α = 20°, the -1^{st}-order amplitude tends towards zero, the ratio of the -1^{st} order to the +1st order is maximal, and the reflected efficiency is equal to 0.3. Contrary to the sinusoidal case, we were unable to find a negligible reflectivity in the lamellar case associated with a high ratio of the -1^{st}-order and the +1st order. Figure 4 shows that with inclined sinusoidal gratings, the diffraction efficiency of the 0th order can approach zero when the ratio of the–1st order to the +1st order is high (Fig. 2b).

Figure 5 presents the vector lines of the Poynting vector for the optimal case of unidirectional SPP excitation by slanted lamellar grating. The color map illustrates the norm of the Poynting vector. The normal incidence can be easily observed in the far-field region, and the excitation as well as the propagation of the SPP by the −1st order are well shown in the near-field region by the bending of the lines to the left, along the metallic surface. SPP propagate with losses, and as a consequence, the lines of energy flows are not strictly parallel to the surface. The norm of the Poynting vector is minimum at the centre of the blue spots which are due to interferences between counter-propagating waves, between the incident and reflected waves around y=650 nm, and between SPP propagating on the positive and negative x axis around y=250 nm. When the amplitude of the counter propagating waves are similar, curls of the Poynting vectors appear around the minima of the norm of the Poynting vector, which tends towards zero at the centre of the curls [20]. But the 0th and +1st reflected orders have been minimized, so that the interference phenomenon is weak and does not perturb the flow lines of the Poynting vector.

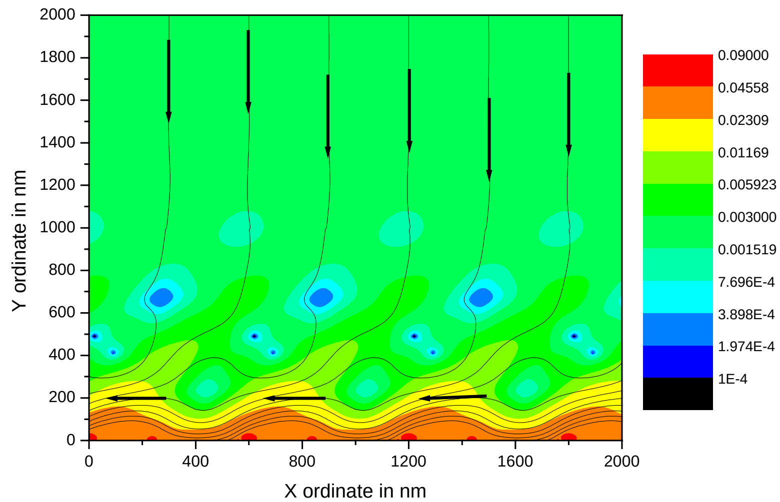


Fig. 5. Colour map: Norm of the Poynting vector, black lines: Lines of energy flow. Five periods are represented, and one line is plotted per period for the same grating as in Fig. 3 (with h = 65 nm, d = 0.6 μm, c = 0.4d, λ = 632.8 nm).

The SPP propagation constant can be calculated numerically by resolving the homogeneous problem with the use of the scattering matrix [17]. The effective index δ is defined as the propagation constant α_P of the SPP normalized by the incident wavenumber: $\delta = \alpha_P/(2\pi/\lambda)$. In the lamellar case, it is equal to 1.038533+i0.02115 and in the sinusoidal case, it is equal to 1.008771+i0.00659. The real and imaginary parts of the SPP propagation constant are smaller in the sinusoidal case due to the absence of metallic edges in the smooth profile. For lamellar profiles, sharp edges perturb the propagation of SPP and decrease their phase velocity (increase of the real part of δ), and are responsible for the radiation of the SPP and increase of ohmic loss when they propagate along the metallic surface which increases the losses leading to higher imaginary part of δ.

It must be stressed that the two counter-propagating SPP have one and the same propagation constant, despite of the asymmetry of the device with respect to the Oy axis. The difference in the coupling strengths to the two counter-propagating SPP modes is due to the different amplitudes of the –1st and +1st orders.

Figure 6 presents the Poynting vectors in the near-field region of an inclined sinusoidal grating with groove height and inclination angle values marked by the cross in Fig. 2b and a SPP effective index equal to $\delta = 1.008771 + i0.00659$. The map of the Poynting vector inside the modulated area, i.e. just above the metallic surface, shows that the smooth sinusoidal profile does not perturb the SPP propagation and allows the energy to flow without curls along the metallic surface. As in Fig. 5, the Poynting vector lines in the far-field region are normal to the grating plane.

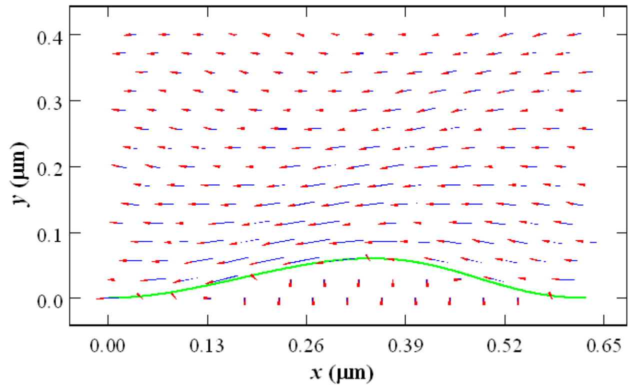


Fig. 6. Poynting vectors plotted in the near field area above a sinusoidal grating illuminated in normal incidence. d = 626.67 nm, α = 27.5 ° and h = 59.94 nm.

3. Conclusion

It has been shown that lamellar and sinusoidal slanting gratings can couple normally incident light to a unidirectional SPP. The excitation in only one direction is not due to a difference between the two propagation constants of the counter-propagating SPP modes (which are identical), but to different coupling strengths between the incident light and the +1st and −1st orders due to the profile asymmetry. A high coupling from the normally incident light to unidirectional SPP requires the reflected 0th and +1st orders be negligible and the −1st order be strong. The two preceding conditions are fully satisfied with slanted sinusoidal gratings and partially satisfied with slanted lamellar gratings. The map of the Poynting vector shows that in the far-field region the energy impinges in normal incidence on the grating, due to the low reflectivity, and that the excitation of one of the two counter-propagating SPP curves the energy flow along the surface of the grating. A map of the Poynting vectors above the smooth inclined sinusoidal profile shows that the electromagnetic energy follows well the metallic surface, without formation of curls, which would appear if the counter-propagating SPP were equally excited. As a conclusion, the slanted grating is a quite simple optical component able to fully convert the incident light into a single SPP and the problem of the reflected light can be avoided by the use of an inclined sinusoidal profile instead of a lamellar one.